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DETERMINATION OF PROPAGATION CONSTANTS IN AN OPTICAL WAVEGUIDE OBTAINED IN GLASS BY DOUBLE ION EXCHANGE

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The finite element method is used to determine the propagation constants in an optical waveguide obtained in glass by double ion exchange (Ag^+). The second diffusion of the Ag^+ ion in glass shifts the electric field peak towards higher values of the depth, in accord with a similar behavior of the refractive index profile maximum.

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1. Introduction

The double ion exchange Ag^+ - Na^+ in glass, by diffusion technique has been found to be a method for fabrication of optical waveguides with a high refractive index region [1].

Recently [1], the maximum refractive index difference profile of the optical waveguides obtained in glass by double ion exchange has been modeled by using Gaussian and complementary error functions.

In this paper the finite element method is used to determine the propagation constants for TE polarization in a waveguide obtained in glass by double ion exchange (Ag^+).

2. Theory

For a wave propagating along the z axis, assuming that the refractive index change is small, the electric field E (x, y) of a mode in a planar glass waveguide is determined by the scalar - wave equation:

$$\frac{\partial^2 E(x,y)}{\partial x^2} + \frac{\partial^2 E(x,y)}{\partial y^2} + \left(k_0{}^2 n^2(x,y) - \beta^2\right) E(x,y) = 0 \qquad (1)$$

where β is the propagation constant, k_0 is the free space wave number and n(x, y) is the refractive index profile [1]:

$$\begin{aligned} &n(x,y) = n_s + \Delta n(x,y) = n_s + \Delta n f(y) g(x), \ \ y > 0, \\ &n(x,y) = n_c \ , y < 0 , \end{aligned} \qquad (2)$$

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$$f(y) = \exp\left(-\frac{(y-y_0)^2}{\left(\frac{\sigma_{y,left} + \sigma_{y,right}}{2} sign(y-y_0) + \frac{\sigma_{y,left} - \sigma_{y,right}}{2} \right)^2} \right), \quad (3)$$

$$g(x) = \frac{\frac{1}{2}\left[erfc\left[\frac{(x-x_0)}{\sigma_x} \right] + erfc\left[\frac{(-x-x_0)}{\sigma_x} \right] \right] - 1}{\max\left\{ \frac{1}{2}\left[erfc\left[\frac{(x-x_0)}{\sigma_x} \right] + erfc\left[\frac{(-x-x_0)}{\sigma_x} \right] \right] - 1 \right\}}, \quad (4)$$

n_s is the index of the substrate, n_c is the index of the cover region, $\sigma_{y,\ left}$ and $\sigma_{y,\ right}$ are the depth variances in the left and right side, with respect to maximum and $n_1 = n_s + \Delta n(0, 0)$ is the maximum value of the refractive-index distribution.

The wave equation (1) for a straight waveguide can be written as an eigenvalue equation (with the eigenvalue - β^2):

$$-\frac{\partial^2 E(x,y)}{\partial x^2} - \frac{\partial^2 E(x,y)}{\partial y^2} - k_0{}^2 n^2(x,y) E(x,y) = \left(-\beta^2\right) E(x,y) \quad (5)$$

which has the same form as the usual Hamiltonian eigenvalue equation.

3. Determination of propagation constants

We have solved the equations (2-4, 5) for the given boundary conditions (the Dirichlet boundary condition for large distances from the waveguide axis where the wave function can be approximated with 0 and the Neuman boundary condition for y = 0) by using the Galerkin's variant of the finite element method, with triangular grid and variable step [2]. For symmetry reasons in a straight waveguide, we can use only the positive part of x but with the Neuman boundary condition for x = 0 and y = 0.

Table 1. The normalized propagation constants b, the propagation constants β (in μm^{-1}), and the effective refractive indices N_m, obtained by using finite element method for the first three modes of a glass waveguide (λ = 0.6328 μm, n_s = 1.513099, n_c = 1, Δn = 0.016609, Δn (0, 0) = 0.016801, n_1 = 1.5297, σ_x = 1.8963 μm, $\sigma_{y,\ left}$ = 3.6579 μm, $\sigma_{y,\ right}$ =1.2692 μm, x_0 = 4.6268 μm, y_0 = 5.7 μm, f = 10 μm, $t_1 = t_2$ = 0.75 min). ΔX (in μm) is the complete width at E = 1/e in the x direction and ΔY (in μm) is the complete width at E = 1/e in the y direction for the fundamental mode TE_0.

	b	β	N_m	ΔX	ΔY
TE_0	0.785039	15.153385	1.526147	5.83	3.26
TE_1	0.557564	15.115960	1.522377		
TE_2	0.486147	15.104191	1.521192		

Also, we have calculated the normalized propagation constant b = $(N_m{}^2 - n_s{}^2) / (n_1{}^2 - n_s{}^2) = 1 - U^2/V^2$, $N_m = \beta / k_0$, where N_m is the effective refractive index, V is the normalized frequency and U is the modal parameter of the index profile.

We have calculated for the first three modes (with the notations from [3-4]) of a glass waveguide (λ = 0.6328 µm, n_s = 1.513099, n_c = 1, Δn = 0.016609, $\Delta n(0,0)$ = 0.016801, n_1 = 1.5297, σ_x = 1.8963 µm, $\sigma_{y,\,left}$ = 3.6579 µm, $\sigma_{y,\,right}$ =1.2692 µm, x_0 = 4.6268 µm, y_0 = 5.7 µm, for a large width of the window f = 10 µm and the diffusion time $t_1 = t_2$ = 0.75 min [1]), the normalized propagation constant b, the propagation constant β, the effective refractive index N_m, the distribution of the electric field E(x, y) and the contour plot of the field profile by using finite element method (Table 1 and Fig. 1).

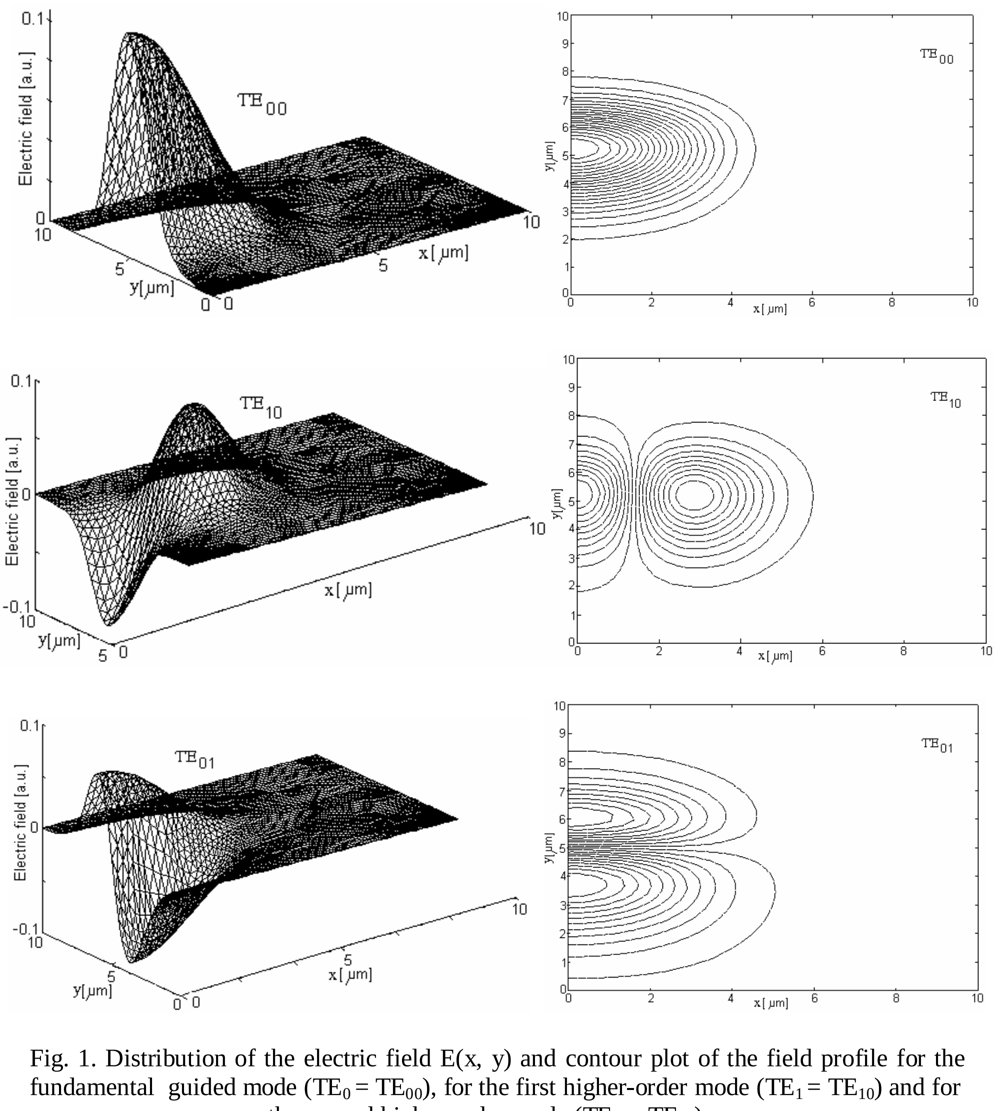

Fig. 1. Distribution of the electric field E(x, y) and contour plot of the field profile for the fundamental guided mode ($TE_0 = TE_{00}$), for the first higher-order mode ($TE_1 = TE_{10}$) and for the second higher-order mode ($TE_2 = TE_{01}$).

The cross sections of the electric field (normalized to a maximum value of 1) at its peak (x = 0, y = 5.2) for the fundamental guided mode and the refractive index profile are given in Figs. 2-3. Also, the complete widths ΔX and ΔY at the 1/e points for the fundamental state are calculated (Table 1) and illustrated in Figs. 2-3.

In a recent paper [5] we have been shown that a subsequent second diffusion of magnesium shifts the electric field peak towards higher values of the depth, which is in accord with a similar behaviour of the refractive index profile maximum. A similar behavior is in our case of the glass waveguide due to the in-diffusion of the first ion in the time t_1 = 0.75 min and the diffusion of the second ion in the time t_2 = 0.75 min (see the Fig. 3 and Ref. [1]).

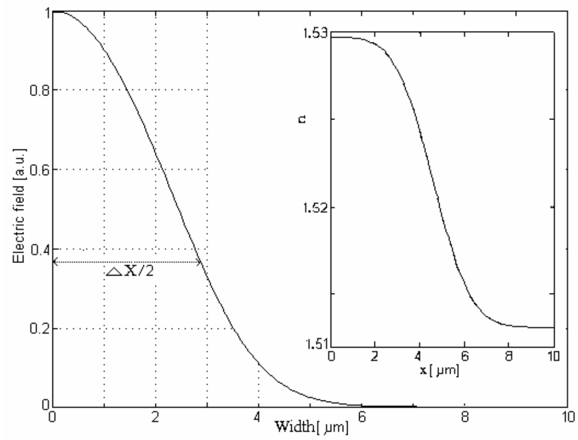

Fig. 2. Cross section of the electric field parallel (width) to the substrate surface for the fundamental state and the width dependence of the refractive index profile. ΔX is the complete width at E = 1/e in the x direction.

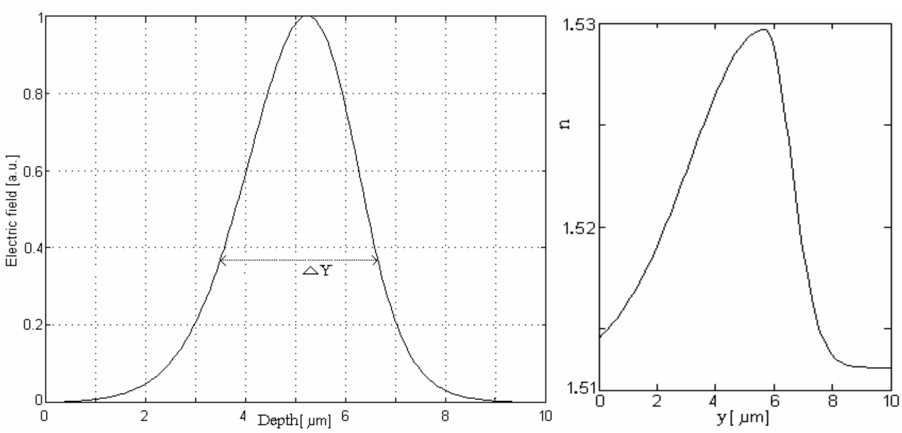

Fig. 3. Cross section of the electric field perpendicular (depth) to the substrate surface for the fundamental state and the depth dependence of the refractive index profile. ΔY is the complete width at E = 1/e in the y direction.

4. Conclusions

In this paper we report some theoretical results concerning the evaluation of the propagation constants for TE polarization in an optical waveguide obtained in glass by double ion exchange (Ag^+). The wave equation was solved using the finite element method for the given boundary conditions (the Dirichlet boundary condition for large distances from the waveguide axis where the wave function can be approximated with 0 and the Neuman boundary condition for y = 0) by using the Galerkin's variant.

The obtained results may be used for the design of several integrated optoelectronic devices

References

[1] N. N. Puscas, J. Optoelectron. Adv. Mater. **2**, 191 (2000).
[2] V. A. Popescu, Phys. Lett. A **297**, 338 (2002).
[3] N. N. Puscas, B. Wacogne, A. Ducariu, B. Grappe, Opt. Quantum Electron. **32**, 1 (2000).
[4] N. N. Puscas, B. Wacogne, A. Ducariu, B. Grappe, J. Modern Optics **46**, 1017 (1999).
[5] V. A. Popescu, Optics Comm., accepted for publication, (2005).